TIME LAGS IN LOW MASS X-RAY BINARIES

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ABSTRACT Using RXTE/PCA data, we have studied the time lag (TL) properties of a sample of four accreting neutron stars (NSs), namely 1E1724-3045, GS1826-238, 4U1705-44 and 4U1728-34. The aim of the study is to identify the spectral and timing state(s) in which TLs are detected. Along this work, we have discovered TLs between the 7-40 keV hard and 2-7 keV soft photons from 4U1728-34 with amplitudes similar to those seen in 4U1705-44 (i.e. ~ 2 ms at 5 Hz). We show that the TLs are only seen in the low states of those sources, but that within the so-called "island" spectral state, some sources display TLs whereas some do not. On the other hand, we have found that TLs are detected when the associated Power Density Spectrum (PDS) shows excess power at high frequencies (above ~ 1 Hz).

KEYWORDS: Stars: individual: 1E1724-3045, GS1826-238, 4U1705-44, 4U1728-34. - X-rays : stars - stars : neutron - stars : binaries.

1. INTRODUCTION

TLs have been reported so far from both accreting black holes (BHs, Cyg X-1, GX339-4) and NSs (4U0614+09, 4U1705-44, Ford et al. 1999). The amplitude of these TLs is typically 20 ms at 1 Hz for NSs and BHs (Ford et al. 1999). The origin of these TLs is currently under debate. Uniform comptonization models predicting constant TLs are however ruled out by the data. Comptonization in a non-uniform medium might account for the observed TLs (Kazanas et al. 1997), but in this case, their magnitude implies that the Comptonizing cloud extends to very large radii, which in turn poses an energy problem. Recently, Poutanen and Fabian (1999) have proposed a "magnetic flare" model that could reproduce the observed PDS and TL magnitude without requiring a large size region.

Using proprietary and archival RXTE/PCA data, we have initiated a systematic study of TLs from NSs, with the aim of determining whether TLs were associated with a singular spectral and/or timing state. We characterize the spectral state of a source using color-color diagrams (CCDs). For the timing state, we compute the PDS over a broad X-ray energy band (2-40 keV). To start with, we have selected two NSs that are always in a low state (1E1724-3045, GS1826-238, Barret et al. 2000), and two that are more variable; undergoing occasionally low states (4U1705-44, 4U1728-34). For the latter sources, we have sampled both their low and high

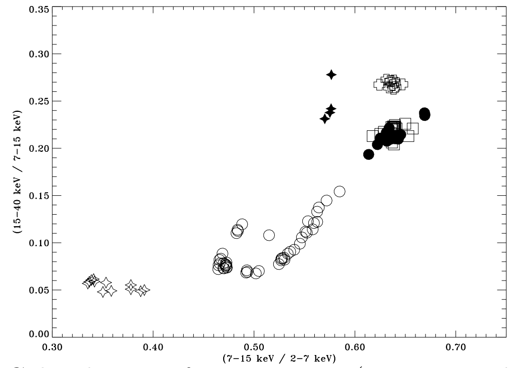

FIGURE 1. Color-Color diagram for 4U1705-44 (stars opened and filled), 4U1728-34 (circles opened and filled), 1E1724-3045 (squares), and GS1826-238 (crosses). Filled symbols correspond to time periods during which TLs were detected. The integration time of each data point is $\sim$ 3000 seconds. For 4U1728-34 and 4U1705-44, both high and low states have been sampled. TLs are only detected in their low states (up right in the figure).

states. Their low state PDS are typical of "island" state PDS, being characterized by a flat top below $\nu_{\rm Break}$ and a broad QPO-like feature in the declining part of the PDS above $\nu_{\rm Break}$ (at $\nu_{\rm QPO}$). TLs were computed using the techniques described in Nowak et al. (1999a) between the 7-40 keV hard and 2-7 keV soft photons.

2. TIME LAGS VERSUS SPECTRAL/TIMING STATE

Figure 1 shows the CCD of the four sources. Fig. 2 shows the corresponding PDS (top) and TL spectra (bottom). TLs were detected only from 4U1728-34 and 4U1705-44, and in their lowest/hardest intensity states (namely their "island" state). This is the first report of TLs from 4U1728-34. No TLs were detected in their high states, with upper limits of 0.1-0.01 seconds between 1 and 10 Hz; i.e. a factor of 10 larger than the values detected during their low states. No TLs were detected from the two steady low state sources, and the upper limits we derived are lower than the observed values for 4U1728-34 and 4U1705-44, indicating that the non detection of similar TLs is not due to a lack of sensitivity.

Looking at Fig. 1 and 2, a few points can be drawn. First, TLs are not associated with a singular spectral state; 4U1728-34 and 1E1724-3045 occupy the same region of the CCD, and only the former shows TLs. Second, although the overall shape of their PDS is broadly similar, there is one noticeable difference that shows up very clearly in the $\nu F\nu$ representation of the PDSs; that TLs are associated with a timing state in which the whole PDS is shifted towards high frequencies ($\nu_{\rm Break}$ and $\nu_{\rm QPO}$ are a factor of 10 larger for 4U1728-34 and 4U1705-44 than for 1E1724-3045 and GS1826-238). Third, when $\nu_{\rm Break}$ and $\nu_{\rm QPO}$ are high, TLs are significantly

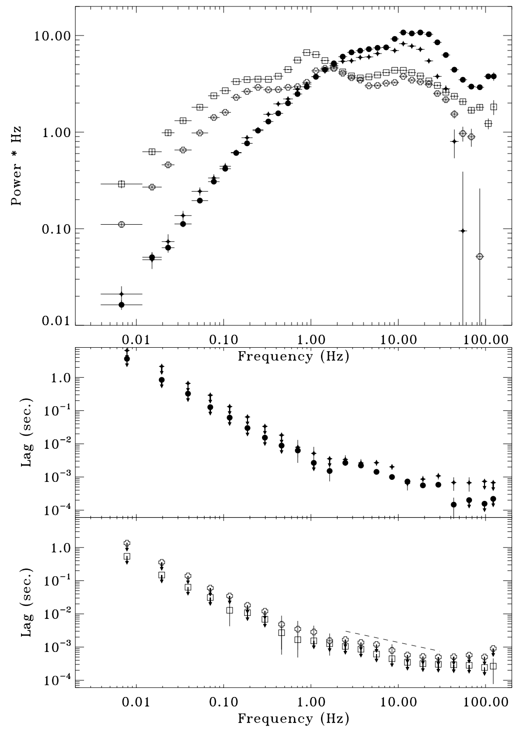

FIGURE 2. *Top panel:* Power Density Spectra, *Bottom panel:* TL spectra for 4U1728-34 and 4U1705-44 (top) and upper limits on TLs for GS1826-238 and 1E1724-3045 (bottom). For indication, the magnitude of the TLs detected from 4U1728-34 and 4U1705-44 is plotted with a dashed line.

detected at frequencies between $\nu_{\rm Break}$ and up to or slightly above $\nu_{\rm QPO}$. Fourth, although of lower significance than the effect observed in the two BHs Cyg X-1 and GX339-4 (Nowak et al. 1999a,b), there is an indication that the TL decreases with frequency, especially for 4U1728-34. Finally, TLs do not depend upon the intensity of the aperiodic variability, as the four PDSs of Fig 2. have comparable integrated RMS (ranging from 17 to 25% in the 2-40 keV band).

3. CONCLUSIONS

We have discovered TLs in the low state of 4U1728-34, and confirmed the previous detection of TLs from 4U1705-44 (Ford et al. 1999). In our attempt to associate the presence of TLs with a singular spectral state, we have shown that for the same spectral state (same position in the CCD) some sources do have TLs whereas some do not. The presence of TLs must thus be tracked somewhere else.

Despite having a limited sample, we have found that TLs are detected when the characteristic low state PDS shows excess power at high frequencies (with a $\nu_{\rm Break} \sim 1$ Hz instead of $\sim 0.1 - 0.2$ Hz). Recently, Pottschmidt et al. (2000)

showed that the shot relaxation time in the hard state of Cyg X-1 (scaling as ${\nu_{\rm Break}}^{-1}$) anticorrelates with the TL amplitude. We cannot test the presence of this effect within the data set used here. However, if the same anticorrelation applies to NSs, it could provide an explanation for the non detection of smaller TLs from the sources with the lowest $\nu_{\rm Break}$. If $\nu_{\rm Break}$ and $\nu_{\rm QPO}$ are somehow related to the position of the inner disk radius within the corona, as possibly suggested by recent observations (Revnivtsev et al. 2000), the closer the disk gets to the central object (i.e the deeper inside the corona), and the larger the TLs are. In this picture, it is interesting to note that this subtle change in the accretion geometry is not reflected in the CCD, implying similar parameters for the Comptonizing cloud and input seed photon energy for all sources.

To conclude, the above study, although not addressing the origin of the TL itself has provided some hints about the conditions under which they are produced. Further work is needed to determine whether TLs are indeed always associated with the peculiar timing state described in this paper. Confirming this result would be extremely valuable for constraining any theoretical models attempting to reproduce the TL properties of these systems.

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